

GAMMA-RAY BURSTS - A PRIMER FOR RELATIVISTS

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Gamma-Ray Bursts (GRBs) - short bursts of 100-1MeV photons arriving from random directions in the sky are probably the most relativistic objects discovered so far. Still, somehow they did not attract the attention of the relativistic community. In this short review I discuss briefly GRB observations and show that they lead us to the fireball model - GRBs involve macroscopic relativistic motion with Lorentz factors of a few hundred or more. I show that GRB sources involve, most likely, new born black holes, and their progenitors are Supernovae or neutron star mergers. I show that both GRB progenitors and the process of GRB itself produce gravitational radiation and I consider the possibility of detecting this emission. Finally I show that GRBs could serve as cosmological indicators that could teach us about the high redshift ($z \approx 5 - 15$) dark ages of the universe.

1 Introduction

Gamma-Ray bursts - GRBs, short and intense bursts of γ -rays arriving from random directions in the sky were discovered accidentally more than thirty years ago. During the last decade two detectors, BATSE on CGRO and BeppoSAX have revolutionized our understanding of GRBs. BATSE has demonstrated ¹ that GRBs originate at cosmological distances in the most energetic explosions in the Universe. BeppoSAX discovered X-ray afterglow². This enabled us to pinpoint the positions of some bursts, locate optical ³ and radio ⁴ afterglows, identify host galaxies and measure redshifts to some bursts ⁵.

The high energy release and the rapid time scales involved suggested very early that GRBs might be associated with relativistic compact objects. The discoveries of BATSE and BeppoSAX confirmed these expectations. These observations have established the Fireball model demonstrating that GRBs are the most relativistic objects known so far:

- GRBs involve macroscopic ultrarelativistic flows with Lorentz factors $\Gamma \geq 100$.
- GRBs involve accretion onto a newborn compact object, most likely a black hole. GRBs are the birth cries of these black hole.
- GRBs could emit significant amounts of gravitational radiation; both in the process of the formation of the black hole and during the acceleration of the matter to relativistic velocities.

- GRB can serve as beacon lights that would help us to explore the high redshift universe.

I review, here, our understanding of GRBs, emphasizing, as appropriate for this conference, their relativistic nature. I begin in with a very brief exposition of the properties of GRBs. I continue in section 3 with a short exposition of the Fireball model (see ^{6,7} for details), focusing on realization that GRBs must involve ultrarelativistic motion and on the observational proofs of such motion. In 4 I summarize the implication of the Fireball model to the “inner engines” and showing their association with black holes. I also discuss the possible progenitors of GRBs. In section 5 I discuss GRBs as sources of Gravitational radiation. I will not discuss here how GRBs could be used to explore the early high z universe and I refer the reader to recent reviews ^{8,9} on this issue. Concluding remarks, predictions and open questions are discussed in section 6.

2 Gamma Ray Bursts Observations

Gamma-Ray Bursts are short and intense bursts of soft gamma-rays, arriving from random directions in the sky. Most observational features of GRBs are nicely summarized in various reviews see e.g. ^{10,11}. Some of the basic features of the prompt burst are:

- The bursts originate from cosmological distances and arrive from random directions in the sky.
- The overall observed fluences range from 10^{-4} ergs/cm² to 10^{-7} ergs/cm² (the lower limit depends of course on the characteristic of the detectors and not on the bursts themselves). This corresponds to isotropic emission of 10^{53} ergs. However, we know today that most GRBs are narrowly beamed and the corresponding energies are around 10^{51} ergs ^{12,13,14}.
- The spectrum is non thermal. The energy flux peaks at few hundred keV and there is a long high energy tail extending in cases up to GeV.
- The duration of the bursts ranges from less than 0.01sec to more than 100sec. GRBs are divided to short ($T < 2$ sec) and long ($T > 2$ sec) according to their duration.
- The light curves show rapid variability, at times on scales less than 10msec.

- The present local rate of long observed GRBs is $\approx 2\text{Gpc}^{-3}\text{yr}^{-1}$ ^{15,16}. The rate of GRBs seems to follow the star formation rate, namely this rate was higher by a factor of 10 at $z > 2$. The rate will of course be higher by a factor $2/\theta^2$, if GRBs are beamed with an opening angle θ .
- The rate of short bursts is uncertain. There are indications that short bursts are weaker than long ones and hence the observed short bursts are nearer to us than the long ones ^{17,18}. The best estimate so far suggests that all short bursts are at $z < 0.5$. So far afterglow was not detected from any short burst and there is no redshift measurement to any short burst hence there is no independent confirmation of this estimate. Given about 250 short bursts per year and assuming that they all come from within $z < 0.5$ we find that the current rate of observed short bursts, $R_{iso-short} = 2 \times 10^{-8}\text{Mpc}^{-3}\text{yr}^{-1}$, is about ten times larger than the rate of long GRBs.

Until 1997 there were no known counterparts to GRBs in other wavelengths. On Feb 28 1997 the Italian-Dutch satellite BeppoSAX detected x-ray afterglow from GRB 970228. The exact position given by BeppoSAX led to the discovery of optical afterglow ³. Radio afterglow was detected in GRB 970508 ⁴. By now more than thirty x-ray afterglows have been observed. About half of these have optical and radio afterglow and in many of those the host galaxy has been discovered and in a dozen or so cases their redshift has been measured. The observed redshifts range from 0.46 to a record of 4.5.

3 Ultra-Relativistic Motion and the Fireball Model

3.1 The Compactness Problem and Ultra-Relativistic Motion

The need for ultrarelativistic motion in GRBs arise from the conflict between the large energy released, the short time scale and the non thermal spectrum. With a fluence of $\sim 10^{-6}\text{ergs/cm}^2$ and a cosmological distance $\sim 10^{28}\text{cm}$ the energy of GRBs is $\sim 10^{51}\text{ergs}$. This energy is released within a few seconds. Using the usual causality limit on the size of an object, R , given a variability time scale, ΔT , $R \leq c\Delta T$ to estimate the density of photons one finds that the optical depth for pair production $\gamma\gamma \rightarrow e^+e^-$ would be $\sim 10^{15}$ (Piran, 1999). Such a source cannot emit the observed nonthermal spectrum.

Already in 1975 Ruderman ¹⁹ pointed out that relativistic effects could eliminate this problem. First if the source is moving relativistically with a Lorentz factor Γ towards us then the usual causality limit is replaced by: $R \leq c\Delta T/\Gamma^2$. Additionally if the source is moving towards us the observed photons

have been blue shifted. At the source they have lower energy which would be insufficient for pair production. Together this leads to a decrease in the estimated optical depth by a factor of $\Gamma^{2+2\alpha}$, where $\alpha \sim 2$ is the spectral index, namely the exponent of the photon number distribution. Various estimates ^{20,21,22,23}, of the Lorentz factor Γ based on the compactness problem lead to comparable values, $\Gamma \geq 100$, (see ²³ for a critical review). Today we have independent direct observational evidence for such ultra-relativistic motion.

3.2 The Fireball Model

While we don't expect celestial objects to roam around at ultra-relativistic velocities one can imagine spherical explosions or jets in which matter is ejected from a central source ultra-relativistically. This leads us to the Fireball model.

The Fireball model asserts that GRBs are produced when the kinetic energy (or Poynting flux) of a relativistic flow is dissipated by shocks. These shocks accelerate electrons and generate strong magnetic fields. The relativistic electrons emit the observed γ -rays via synchrotron or Synchrotron-self Compton. There are two variants of this model: The External Shocks model ²⁴ assumes that the shocks are between the relativistic flow and the surrounding circumstellar matter. The Internal Shocks model ^{25,26} assumes that the flow is irregular and the shocks take place between faster and slower shells within the flow. The rapid time variability seen in most GRBs cannot be produced by external shocks ^{27,28}. This leaves internal shocks as the only viable model for the production of the GRB. As internal shocks do not dissipate all the kinetic energy, the remaining energy will be dissipated later by interaction with the surrounding matter and produce an afterglow. This leads us to the Internal-External shocks model ²⁷. According to this model Internal shocks are responsible for the GRB while external shocks produce the longer lasting afterglow (see Fig. 1). The shocks occur at relatively large distances ($10^{13} - 10^{14}$ cm for internal shocks and $10^{14} - 10^{18}$ cm for external shocks) from the source that generates the relativistic flow. The observed radiation from the GRB or from the afterglow reflects only the conditions within these shocks. We have only indirect information on the nature of the "inner engines".

Fig. 1 depicts a schematic picture of the Internal-External shocks model. An inner engine produces an irregular wind. The wind varies on a scale δt and its overall duration is T . The variability scale δt corresponds to the variability scale observed in the GRB light curve ²⁹ thus, $\delta t \leq 1$ sec. Internal shocks take place at $R \approx \delta t \Gamma^2 \approx 3 \cdot 10^{14}$ cm $(\delta t/1 \text{ sec})(\Gamma/100)^2$. External shocks become significant at $\sim 10^{16}$ cm (see ^{30,6} for details). Initially, there is also a

The Internal-External Scenario

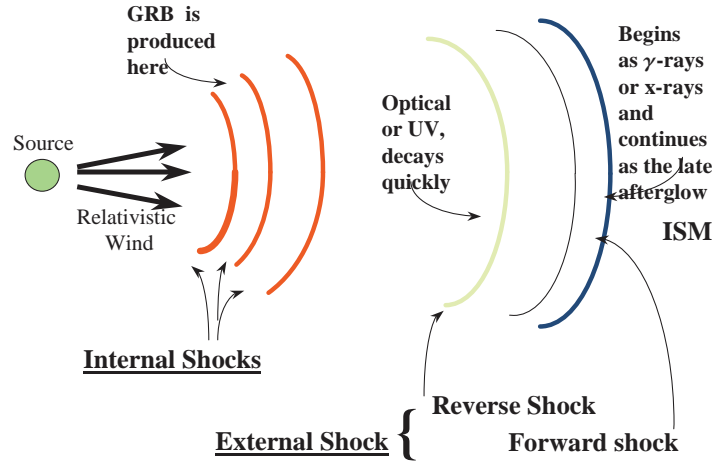


Figure 1. **The External Shocks Model.**

short lived reverse shock that propagates into the ejecta. This reverse shock is responsible to the prompt optical emission observed in GRB990123 that we discuss later

The forward shock propagates into the surrounding matter producing the afterglow. It turns out to a blast wave that is well described by the Blandford-McKee self similar solution. The theory of the afterglow is well understood³¹. Blandford and McKee have worked out (already in the seventies!) the theory of an adiabatic relativistic blast wave. This is the relativistic analog of the well known Sedov-Taylor solution. Electrons are accelerated to relativistic velocities by the shocks and their interaction with the magnetic field leads to synchrotron radiation. This provides an excellent model for the observed emission³². Overall we have a simple theory characterized by five parameters: the total energy, E_0 , the ambient density, n_0 , the ratio of the electrons and magnetic fields energy density to the total energy density, ϵ_e , ϵ_B and the exponent of the electrons' energy distribution function p . An additional sixth parameters, the exponent of the circumstellar density distribution, n , arises

in cases when the external matter density is inhomogeneous ($\rho \propto r^{-n}$). Most notable is $n = 2$ corresponding to a pre-GRB wind expected in some models³³. This rather simple theory predicts a robust relations between α and β the exponents describing the flux as a function of frequency, $F_\nu \propto t^{-\alpha} \nu^{-\beta}$. At the high frequencies, above the cooling frequency, we have (for $n = 0$), $\alpha = (3p - 2)/4$ and $\beta = p/2$.

3.3 Observations of Relativistic Motion

The radio afterglow observations of GRB 970508 provided the first verification of relativistic motion. The radio light curve (in 4.86GHz) varied strongly during the first month. These variations died out later. Even before this transition Goodman³⁴ interpreted these variations as scintillations. The observation of a transition after one month enabled Frail et al.,⁴ to estimate the size of the afterglow at this stage as $\sim 10^{17}$ cm. It immediately follows that the afterglow has expanded relativistically. Additionally, the source is expected to be optically thick in radio³⁵ leading to a ν^2 rising spectrum at these frequencies. The observed flux from the source enables us (using the black body law) to estimate the size of the source. As predicted the radio spectrum increases like ν^2 . The size estimated with this method agrees⁴ with the one derived by the scintillations estimate implying as well a relativistic motion.

The radio emission from GRB970508 showed relativistic motion in its afterglow. However, these observations took place one month after the burst and at that time the motion was only “mildly” relativistic with a Lorentz factor of order a few. Are there “direct” observations for the ultrarelativistic motion that exists earlier?

In Jan 23 1999 ROTSE recorded six snapshots of optical emission from GRB990123³⁶. Three of those were taken while the burst was still emitting γ -rays. The other three snapshots spanned a couple of minutes after the burst. The second snapshot, taken 70sec after the onset of the burst corresponds to a 9th magnitude signal. A comparison of these optical observations with the γ -rays and X-rays light curves (see e.g.⁷) shows that the optical emission does not correlate with the γ -rays pulses. The optical photons and the γ rays are not emitted by the same photons^{37,36}.

How can one explain this flash? The collision between the ejecta and the surrounding medium produces two shocks. The outer forward shock propagates into the ISM. This shock develops later into the self similar Blandford-McKee³¹ blast wave that drives the afterglow. A second shock, the reverse shock, propagates into the flow. This reverse shock is short lived. It dies out

when it runs out of matter as it reaches the inner edge of the flow. While it is active, it is a powerful source of energy. Comparable amounts of energy are dissipated by the forward and by the reverse shocks³⁰. Sari and Piran³⁸ predicted (just a few month before GRB990123) that this reverse shock will produce an intense (brighter than 11th magnitude) prompt optical flash.

The observations of an optical flash demonstrated a relativistic motion with $\gamma \sim 200$ during the burst. There are three independent estimates of the Lorentz factor at the time that the ejecta hits first the ISM³⁷. First the time delay between the GRB and the optical flash suggests $\Gamma \sim 200$. The ratio between the emission of the forwards shock (x-rays) and the reverse shock (optical) gives another estimate of $\Gamma \sim 70$. Finally the fact that the maximal synchrotron frequency of the reverse shock was below the optical band led to $\Gamma \sim 200$. The agreement between these three crude and independent estimates is reassuring.

3.4 Jets, Beaming and Energetics

With redshift measurements it became possible to obtain exact estimates of the total energies involved. While the first burst GRB970508 required a modest value of $\sim 10^{51}$ ergs, the energies required by other bursts were alarming, 3×10^{53} ergs for GRB981226 and 4×10^{54} ergs for GRB990123, and unreasonable for any simple compact object model. These values suggested that the assumed isotropic emission was wrong and GRBs are beamed. Significant beaming would of course reduce, correspondingly the energy budget.

Beaming was suggested even earlier as it arose naturally in some specific models. For example the binary neutron star merger has a natural funnel along its rotation axis and one could expect that any flow would be emitted preferably along this axis. The Collapsar model, in which the GRB is produced during the collapse of a massive star, also requires beaming. Only a concentrated beamed energy could drill a whole through the stellar envelope that exists in this model.

Consider a relativistic flow with an opening angle θ . As long as $\theta > \Gamma^{-1}$ the forwards moving matter doesn't "notice" the angular structure and the hydrodynamics is "locally" spherical³⁹. The radiation from each point is beamed into a cone with an opening angle Γ^{-1} . It is impossible to distinguish at this stage a jet from a spherical expanding shell. When $\theta \sim \Gamma^{-1}$ the radiation starts to be beamed sideways. At the same time the hydrodynamic behaviour changes and the material starts expanding sideways. Both effects lead to a faster decrease in the observed flux, changing α , the exponent of the decay rate of the flux to: $\alpha = p/2$. Thus we expect a break in the light

curve and a new relation between α and β after the break^{40,41,42}. The break is expected to take place at $t_{jet} \approx 6.2(E_{52}/n_0)^{1/3}(\theta/0.1)^{8/3}\text{hr}$ ⁴¹. The magnitude of the break and the time of the transition are different if the jet is expanding into a wind with r^{-2} density profile⁴³. Recently numerical simulation⁴⁴ have shown that the break appears in a more realistic calculations, even though the numerical results suggest that the analytical model developed so far are probably too simple.

GRB980519 had unusual values for $\alpha = 2.05$ and $\beta = 1.15$. These values do not fit the "standard" spherical afterglow model^a. However, these values are in excellent agreement with a sideways expanding jet⁴¹. The simplest interpretation of this data is that we observe a jet during its sideways expansion phase (with $p = 2.5$). The jet break transition from the spherical like phase to this phase took place shortly after the GRB and it was not caught in time. The light curves of GRB990123 shows, however, a break at $t \approx 2\text{days}$ ⁴⁵. This break is interpreted as a jet break, corresponding to an opening angle $\theta \sim 5^\circ$. Another clear break was seen in GRB990510^{46,47}.

The brightest bursts, GRB990123 and GRB980519 gave the first indications for jet like behaviour⁴¹. This suggested that their apparent high energy was due to the narrow beaming angles. A compilation of more bursts with jet breaks suggests that all bursts have a comparable energy $\sim 10^{51}\text{ergs}$ and the variation in the observed energy is mostly due to the variation in the opening angles θ ^{12,13,14}.

3.5 Variability, Internal Shocks and a "NO GO Theorem"

According to the internal shocks model the observed light curve corresponds to the temporal activity of the "inner engine"²⁹. Further indication for this understanding arise from the observations that the distribution of pulse width and pulse separations are similar and that pulse widths are correlated with the intervals preceding of following them⁴⁸.

These results imply that there must be two different time scales operating within the "inner engine". The short time scale is the variability time scale. The duration of the observed burst corresponds to the time that the "inner engine" is active. This time scale is up to 5 orders of magnitude longer than the short, variability scale. This leads us to a NO GO Theorem. One cannot produce a variable GRB by a single explosion in which all the energy is released at once. This NO GO theorem rules out dozens of GRB models (such as evaporating black holes, vacuum instability, transition from a neutron star to a strange star etc...) which involve sudden energy release.

^aA possible alternative fit is to a wind ($n=2$) model but with a unusual high value of $p = 3.5$

4 Black Holes, the Inner Engines and GRB Progenitors

The Fireball model tells us how GRBs operate. However, it does not answer the most interesting astrophysical questions: what produces them and how? I turn to this issues now.

GRBs must involve compact objects. There is no other way to extract so much energy, $\sim 10^{51}$ ergs, so quickly. We have seen earlier that the temporal behaviour puts some stronger limits on the source. The short time scale, which is as short as a few ms, also suggest that we are dealing with a compact object. The long duration of the bursts shows that the source must be active much longer than its dynamical time scale. This suggests that GRBs arise due to accretion and this time scale is the duration of the accretion process. The energy involved requires a massive ($\sim 0.1 - 0.2m_{\odot}$) disk. Such a massive disk can form only as debris during the formation of the compact object itself. With such a massive disk the most likely compact object is therefore a newborn black hole. A black hole is also the natural consequence of the two most common progenitors: Collapsars and neutron star mergers.

Accretion is needed to produce the two different time scales, and in particular the prolonged activity. A massive ($\sim 0.1m_{\odot}$) disk is required because of the energetics. We expect that such a massive disk can form only simultaneously with the formation of the compact object. This leads to the conclusions that GRBs accompany the formation of black holes. This model is supported by the observations of relativistic (but not as relativistic as in GRBs) jets in AGNs, which are powered by accretion onto black holes. This system is capable of generating collimated relativistic flows even though we don't understand how.

An important alternative to accretion is Usov's model ⁴⁹ in which the relativistic flow is mostly Poynting flux and it is driven by the magnetic and rotational energies of a newborn rapidly rotating neutron star. However this model seems to fall short by an order of magnitude of the energy required. Additionally, there is no indication of the slowing down pattern (that would be expected in such a case) in the light curves of GRBs.

4.1 GRB progenitors

Several scenarios could lead to a black hole - massive accretion disk system. This could include mergers (NS-NS binaries ^{50,25}, NS-BH binaries ⁵¹ WD-BH binaries ⁵², BH-He-star binaries ⁵³) and models based on "failed supernovae" or "Collapsars" ^{54,55,56}. Narayan et al. ⁵⁷ have recently shown that accretion theory suggests that from all the above scenarios only Collapsars could pro-

duce long bursts and only NS-NS (or NS-BH) mergers could produce short bursts.

Additional indications on the astrophysical nature of the sources arise from afterglow observations. One has to use these clues with care. Not all GRBs have afterglow (for example, so far afterglow was not detected from any short burst) and it is not clear whether these clues are relevant to the whole GRB populations. These clues seem to suggest a GRB-SN connection:

- **SN association:** Possible association of GRB980425 with SN98bw⁵⁸ and possible SN signatures in the afterglows of GRB970228⁵⁹ and GRB980326⁶⁰.

- **Iron lines:** have been observed in some x-ray afterglows⁶¹. Any model explaining them requires a significant amounts of iron at rest near those GRBs.

- **Association with Star formation:** GRBs seem to follow the star formation rate. GRB are located within star forming regions in star forming Galaxies⁵⁵.

- **GRB distribution:** GRBs are distributed within galaxies. There is no evidence for GRBs kicked out of their host galaxies⁶² as would be expected for NS-NS mergers²⁵.

All these clues point out towards a SN/GRB association and towards the Collapsar model. However, the situation is not clear cut. The association of GRB980425 with SN98bw is uncertain. There are alternative explanations to the bumps in the afterglows of GRB970228 and GRB980326⁶³. Iron is produced in Supernovae. But there is no simple explanation what is iron at rest doing around the GRB (A model that explains the formation of iron lines requires that the supernova took place several month before the burst⁶⁴. This would be incompatible with the reported SN bumps which coincide with the GRB). One should bear in mind that association with star formation and the distribution of GRBs within galaxies indicates that GRB stellar progenitors are short lived. This is compatible with massive stars. However, one cannot rule out a short lived binary NS population⁶⁵ which would mimic this behaviour.

We stress that there are some indication that seem incompatible with the SN association:

- **No Windy Afterglow:** No evidence for a wind ($n=2$) in any of the afterglow light curves. Such winds are expected from massive progenitors. Furthermore, most fits for the afterglow parameters show low ambient density¹³.

- **No Jets:** Some GRBs dont show evidence for a jet or have very wide opening angles¹³, this would be incompatible with the Collapsar model.

5 Gravitational Radiation from GRBs

The appearance of relativistic nonspherical (jets) motion and the association with black holes suggests that GRBs are be potential sources of gravitational radiation. There are two phases in which gravitational radiation can arise in GRBs. First from the process that lead to the formation of the black hole and second from the fireball process itself.

I consider first gravitational radiation that arises before the GRB, as part of the formation of the “inner engine”. Here I consider the two main progenitors candidates: Collapsar and neutron star mergers.

5.1 Mergers

I consider here both binary neutron star mergers and black hole-neutron star mergers under the single category of mergers. These sources are the “canonical” sources of gravitational radiation emission. Both LIGO and VIRGO aim in detecting these sources. Specifically the goal of these detectors is to detect the characteristic “chirping” signals arising from the in-spiraling phase of these events. The possibility of detection of such signals has been extensively discussed (see e.g. ⁶⁶) and we won’t repeat this here. Such events could be detected up to a distance of $\sim 20\text{Mpc}$ with LIGO I and up to $\sim 300 - 600\text{Mpc}$ with LIGO II.

The detection of the chirping merger signal is based on fitting the gravitational radiation signal to pre-calculated templates. Kochanek and Piran ⁶⁷ suggested that the detection of a merger gravitational radiation signal would require a lower S/N ratio if this signal coincides with a GRB. This could increase somewhat the effective sensitivity of LIGO and VIRGO to such events.

It is expected that mergers (either binary neutron star or a black hole-neutron star mergers) produce the short GRBs (see ⁵⁷). Considering the isotropic rate of short GRBs estimated earlier we find that there should be one short burst per year within $\sim 450\text{Mpc}$. This is just at the sensitivity level of LIGO II. As already mentioned it is not clear if short GRBs are beamed. If they are beamed, with the same beaming factor as long GRBs we should expect several hundred mergers events per a single observed burst. This would put one merger event per year at $\sim 80\theta_{0.1}^2\text{Mpc}$.

The corresponding distances to long GRBs are much longer. The nearest (long) GRB detected within a year would be at 1Gpc . This is far beyond the sensitivity of even LIGO II. Beaming puts the nearest (long) event much nearer, at $135\theta_{0.1}^2\text{Mpc}$, well within the sensitivity of LIGO II. However, this burst would be, most likely, directed away from us and won’t be observed

as a GRB. Still a GRB that is beamed away from us is expected to produce an “orphan” afterglow and the gravitational radiation signal could trigger a search for this afterglow.

5.2 Collapsars

The Collapsar model ^{54,56} is based on the collapse of the core of a massive star to a black hole surrounded by a thick massive accretion disk. The accretion of this disk onto the black hole, is accompanied by the acceleration of ultra relativistic jets along the rotation axis and powers the GRB. The jets first have to punch a hole in the stellar envelope. The GRB forms only after the jets have emerged from the envelope. Due to the relatively long time that it takes for the jets to punch a hole in the envelope it is expected that Collapsars can produce only long bursts.

As far as gravitational radiation is concerned this system is very similar to a regular supernova. Rotating gravitational collapse has been analyzed by Stark and Piran ⁶⁸. They find that the gravitational radiation emission emitted in a rotating collapse to a black hole is dominated by the black hole’s lowest normal modes, with a typical frequency of $\sim 20c^3/GM$. The total energy emitted is:

$$\Delta E_{GW} = \epsilon M c^2 = \min(1.4 \cdot 10^{-3} a^4, \epsilon_{\max}) M c^2, \quad (1)$$

where a is the dimensionless specific angular momentum and ϵ_{\max} is a maximal efficiency which is of the order a few $\times 10^{-4}$. The expected amplitude of the gravitational radiation signal, h , would be of the order of $\sqrt{\epsilon} GM/c^2 d$ where d is the distance to the source. Even LIGO II won’t be sensitive enough to detect such a signal from a distance of 1Gpc or even from 100 Mpc. Furthermore, this signal would be rather similar to a supernova gravitational radiation signal. As regular supernovae are much more frequent it is likely that a supernova gravitational radiation signal would be discovered long before a Collapsar gravitational radiation signal.

5.3 Gravitational Radiation Emission from the GRB Itself

I turn now to examine the gravitational radiation that would arise from the GRB process itself. According to the fireball model the “inner engine” accelerates a mass of $M = E/\Gamma c^2$ to a Lorentz factor Γ . The most efficient generation of gravitational radiation could take place here during the acceleration phase, in which the mass is accelerated to a Lorentz factor Γ . To estimate this emission we follow Winberg’s ⁶⁹ analysis of gravitational radiation emitted from a relativistic collision between two particles.

I consider the following simple toy model. Two particles at rest with a mass M are accelerated instantly at $t = 0$ to a Lorentz factor Γ and energy E . Conservation of energy requires that some (actually most) of the rest mass was converted to kinetic energy during the acceleration and the rest mass of the accelerated particle is $m = E/\Gamma = M/\Gamma$. Using the formalism developed by Weinberg⁶⁹ to estimate the gravitational radiation generated in particle collisions, we calculate the gravitational radiation emitted by this system. Prior to the acceleration the two particles has momenta $m_0(1, 0, 0, 0)$. After the acceleration the particles' momenta is $m\Gamma(1, \pm\vec{\beta})$. The energy emitted per unit frequency per unit solid angle in the direction at an angle α relative to $\vec{\beta}$ is:

$$\frac{dE}{d\Omega d\omega} = \frac{GM^2\beta^2}{c\pi^2} \left[\frac{\Gamma^2(\beta^2 - \cos^2 \alpha)}{(1 - \beta^2 \cos^2 \alpha)^2} + \frac{\cos^2 \alpha}{\Gamma^2(1 - \beta^2 \cos^2 \alpha)^2} \right]. \quad (2)$$

The result is independent of the frequency, implying that the integral over all frequency diverges. This nonphysical divergence arises from the nonphysical assumption that the acceleration is instantaneous. In reality this acceleration takes place over a time δt , which is of order 0.01sec. This would produce a cutoff $\omega_{max} \sim 2\pi/\delta t$ above which Eq. 2 is not valid. The angular distribution found in Eq. 2 is dissppointing. The EM emission from the ultrarelativistic source is beamed forwrds into a small angle $1/\Gamma$, enhancing the emission in the forwards direction by a large factor (Γ^2). We find here that the gravitational radiation from this relativistic ejecta is spread rather uniformly in almost all 4π directions. Instead of beaming we have “anti-beaming” with no radiation at all emitted within the forward angle Γ^{-1} along the direction of the relativistic motion.

Integration of the energy flux over different directions yields:

$$\frac{dE}{d\omega} = \frac{GM^2}{c\pi^2} \left[2\Gamma^2 + 1 + \frac{(1 - 4\Gamma^2)}{\Gamma^2\beta} \text{ArcTang}(\beta) \right]. \quad (3)$$

As expected the total energy emitted is proportional to $m^2\Gamma^2$. Further integration over frequencies up to the cutoff $2\pi/\delta t$ yields:

$$E \approx \frac{2GM^2\Gamma^2}{c\pi\delta t}. \quad (4)$$

In reality the situation is much more complicated than the one presented here. First, the angular width of the emitted blobs is larger than Γ^{-1} . The superposition of emission from different directions washes out the no emission effect in the forward direction. Additionally according to the internal shocks model the acceleration of different blobs go on independently. Emission from

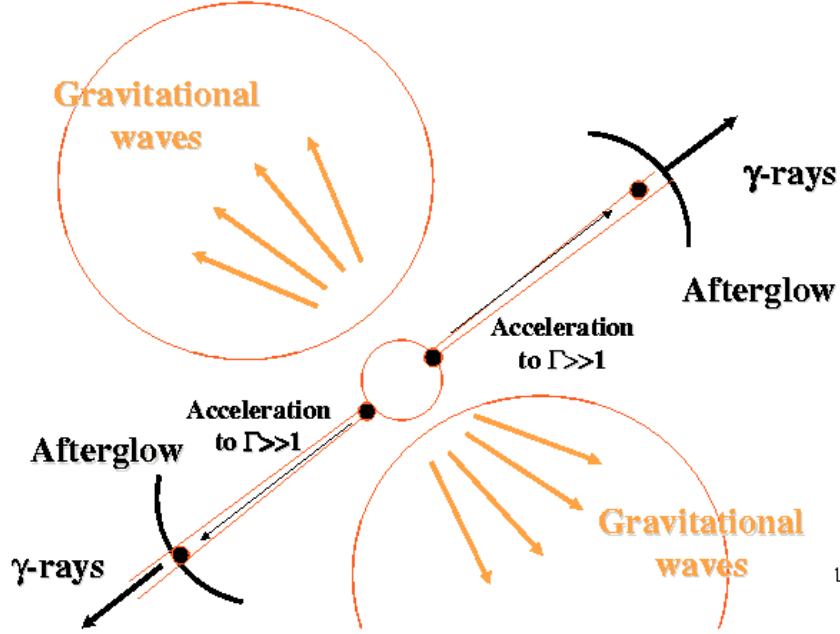


Figure 2. Gravitational waves are mostly orthogonal to the direction of the GRB and the afterglow.

different blobs should be combined to get the actual emission. Both effects *reduce* the effective emission of gravitational radiation and makes the above estimate an upper limit to the emission that is actually emitted.

The gravitational signal is spread in all directions (apart from a narrow beam along the direction of the relativistic motion the GRB). It ranges in frequency from 0 to $f_{max} \approx 100\text{Hz}$. The amplitude of the gravitational radiation signal at the maximal frequency, $f_{max} \approx 100\text{Hz}$, would be: $h \approx (GM\Gamma^2/c^2d)$. For typical values of $E = M\Gamma = 10^{51}$ ergs, $\delta t = 0.01$ sec and a distance of $500Mpc$, we find $h \approx .5 \times 10^{-25}$. This is far below the sensitivity of planned gravitational radiation detectors. Even if we consider a burst which is ten times nearer this "direct" gravitational radiation signal would still be undetectable.

6 Conclusions, Predictions and Open Questions

There is an ample observational support For the Fireball model. Still there are many open questions. The most interesting ones, from the point of view of this conference is how does the black hole based, inner engine, operate. What is the energy source. How does it convert the energy to ultra-relativistic flow and how does it collimate the flow to narrow jets. These interesting issues might be related to the Blandford-Znaek mechanism of extracting energy from a rotating black hole via magnetic processes^{70,71,72,73}. It is a unique challenge to relativists to explore the electrodynamics of black hole and determine under what conditions this process can operate effectively.

We know how GRBs are produced. We are less certain what produces them. We can trace backwards the evolution at the source from the observations of the emitting regions to an accretion disk - black hole system. The traces from this point backwards are less clear. Theoretical considerations⁵⁷ suggest that only Collapsars can produce the disk-black hole systems needed for long bursts while only NS-NS (or possibly NS-BH) mergers can produce the systems needed for short bursts. These conclusions are supported by afterglow observations that suggest SN/GRB association for the long burst population. However, the picture is far from clear yet.

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